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ON LIGHTNING PROTECTION WITH A "REMOTE LIGHTNING ROD"

B. Walter

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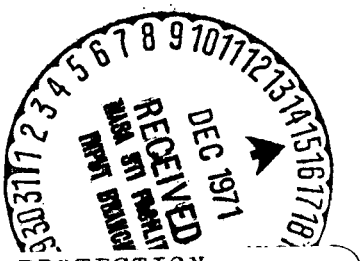

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ON LIGHTNING PROTECTION WITH A "REMOTE LIGHTNING ROD"*

B. Walter

ABSTRACT. Disadvantages of the present type of lightning protection are discussed. It is concluded by means of tests and from lightning statistics that lightning rods separate from the building to be protected offer the best protection.

1. Disadvantages of the Present Type of Lightning Protection for Buildings

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The present generally used type of lightning protection for buildings consists of an intersecting wire running along the ridge-line of a building, with one or more ground leads. This type of lightning protection has no doubt greatly diminished the damage due to lightning, but still has two disadvantages. One of these is that the lightning bolt strikes directly above the roof of the house. The other is that it is often conducted away dangerously near the inhabitants of the house.

With respect to the latter point, for instance, item No. 967 in H. Brodersen's collection of lightning data(1) states that, in a house provided with lightning rods, two persons were stunned by a stroke properly conducted to ground. Also, as No. 1800, it was stated that a cow in a barn "not withstanding the excellent condition of the lightning rod" was actually killed by lightning, although the building suffered no damage.

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*From the National Physical Institute, Hamburg.

**Numbers in the margin indicate pagination in the original foreign text.

(1) Hans Brodersen: Report on Lightning Strokes during the Years 1884-1899 in the Province of Schleswig-Holstein. Kiel, 1909.

The first disadvantage of this type of lightning protection, i.e., the fact that the lightning strikes directly above the roof, is primarily of importance for buildings with thatched roofs. For one thing, incandescent metal fragments melted at the point of the strike, falling into the roof, could easily set it afire. For another thing, it is possible for the discharge to induce currents in the iron wires holding the roof together. This, of course, usually also leads to ignition of the roof.

If we examine Brodersen's collection in this respect, we find among /119
the data 25 lightning strikes which happened in buildings with thatched roofs, and which had lightning conductors of the usual type. Ten of these, or 40%, were set afire. Although that author considers it probable that ignition in most cases was due to improper manufacture or installation of the lightning conductor, this cannot be maintained in every case. In one case (No. 2116), the system in question had been tested shortly before.

2. Definition of a "Remote Lightning Rod". Test of the Range of Protection Theory for Such a Lightning Rod

It is reasonable to raise the question of whether lightning protection of a building cannot also be attained with a lightning rod which is not connected with the building to be protected. Apparently, it must consist of one or more pole-shaped intersecting structures in the vicinity of the building, of such a height that the building is fully protected by this structure.

To be sure, such a "remote lightning rod system" will usually be more expensive than the currently used lightning rod systems. But it is also conceivable that they could even be cheaper, as under some circumstances they can simultaneously protect several adjacent buildings, like all the buildings of a country farm. As we shall see below, at a sufficient height and appropriate location of the intersecting structure, it could even

protect all the buildings of a small town or a certain part of a large city.

Now the first question which we meet for the new type of lightning protection to be considered here is: What is the distance at which a vertical metal pole, set in the earth and well grounded, of certain height and adequate cross sectional area, will protect its surroundings from lightning strokes?

If we attempt first to answer this question theoretically, it seems obvious to use the assumption that the lightning stroke seeks out that point of the Earth's surface which is nearest to the place at which it leaves the storm cloud. Then if we assume further, which is rather incidental, that the exit points for all the lightning bolts leaving such a cloud and passing to the earth lie in a plane WW (Figure 1) which is parallel to the surface of the earth, EE, then it is easy to see that, at least in the plane of the drawing, the protection range CC' of the lightning rod FS is obtained by finding the points P and P', so that circles drawn about P or P' with PS or P'S as radius just touch the earth's surface.

That is, all strokes leaving the cloud at points between points P and P' in the drawing will, by our assumption, seek out the point S. All those strokes leaving the cloud outside section PP' will strike points of the earth's surface left of C or right of C'. Thus the segment CC' is in fact protected from lightning strokes.

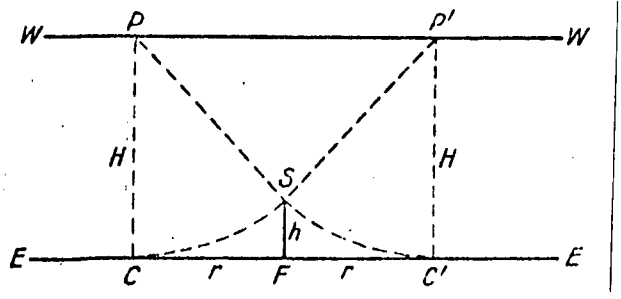

Figure 1. Theoretical derivation of the radius r of the circle of protection of the lightning rod FS.

But the conclusion we have derived for the plane of the drawing in Figure 1 naturally also applies for any other plane through FS. Thus, if our theory is correct, the protective action of the lightning rod FS must extend to all points on the

earth's surface lying within a circle drawn about F with FC as the radius. In other words, FC = r will be the radius of the protective circle of the lightning rod.

Now, if we designate the height of the storm cloud above the earth's surface as H and the height of the lightning rod FS as h, it follows from Figure 1 that

$$r = \sqrt{(2H - h) \cdot h}. \qquad (1)$$

Values of r are summarized in Table 1 for the three cloud heights, H = 1,000 m 2,000 m, and 3,000 m, as well as for a larger series of lightning rod heights, h, between 20 and 300 m. The values are calculated from Formula (1). For example, we find from this that the protective effect of a lightning rod rising 20 m above its surroundings will extend for more than ten times this height. One rising 100 m above its surroundings will have a protective range more than four times its height above the surroundings.

TABLE 1. VALUES CALCULATED ON THE BASIS OF OUR THEORY FOR THE RADIUS, r, OF THE PROTECTIVE CIRCLE OF A SIMPLE, POLE-SHAPED LIGHTNING ROD OF HEIGHT H FOR THREE STORM CLOUD HEIGHTS, H = 1,000 m, 2,000 m, AND 3,000 m. /120

H =	1000 m	2000 m	3000 m
	r =		
h = 20 m	200	280	350
40 „	280	400	490
60 „	340	490	600
80 „	390	560	690
100 „	440	630	770
120 „	480	680	840
140 „	510	730	910
160 „	540	780	970
180 „	570	830	1030
200 „	600	880	1080
250 „	660	970	1200
300 „	710	1050	1310

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3. Test of the Theory by Means of Lightning Strike Statistics from the Hamburg Fire Insurance Office

The findings of the "Hamburg Fire Insurance Office" on buildings damaged by lightning strikes in our city during the years 1912 - 1932 are very appropriate for testing the values of the protective radius of a simple, pole-shaped lightning rod. We can determine from them the extent of protective effect of the city tower. It is quite high and, of course, completely provided with lightning rods. It is compulsory for all the residences of our city to be insured at that office. It compensates for lightning damage as well as for fire damage, and these cases are basically investigated by the office. Thus we can assume that the office's statistics in this respect, even though they obviously do not cover all the strokes striking the city, must provide a very good survey of their distribution in the different parts of the city.

I wish to thank the president of the office Professor Riebesell, who cooperated with me in the most friendly way. On a 1:10,000 map covering the heavily built-up part of our city, he had plotted all the lightning damages established by the office in the period mentioned. There were 438 of these cases. The area of the region considered is 2,640 hectares. Thus, over the 21 years, there was an average of 1.20 lightning strokes per 10 hectares.

The part of the map showing the inner city of the Hamburg region is of particular interest for us, because the highest tower of the city is here. For this reason, only part of Professor Riebesell's map is reproduced in Figure 2. For better clarity, the streets are not shown. The buildings damaged by lightning strokes during the period are marked with heavy crosses and the date of the strike. Prominent high towers are shown by double circles. The watercourses in the city are shown, along with a large number of points, each surrounded with a small circle, showing the height of the ground in meters above the standard zero. Beside each of the towers

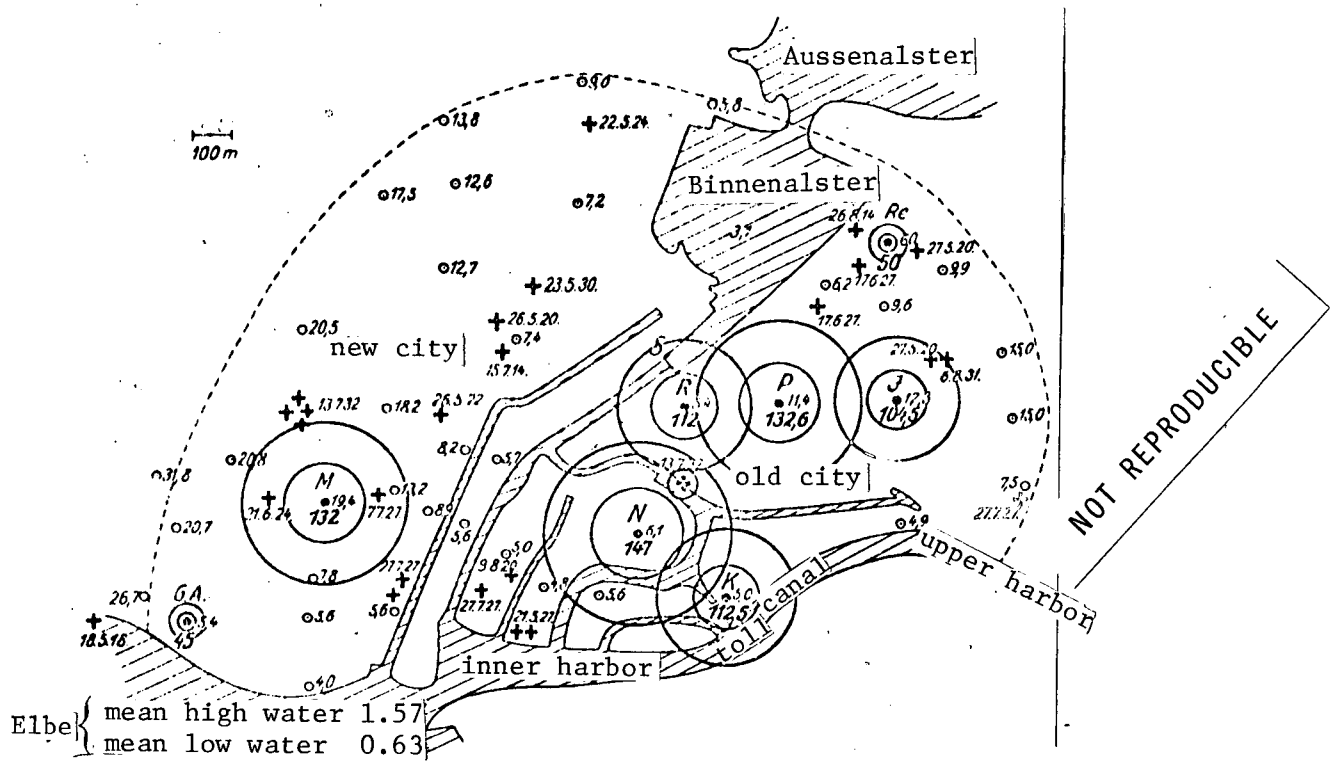

Figure 2. Map of the inner city of Hamburg showing the buildings struck by lightning in the years 1912–1932 (+) as well as the towers (●) and waterways in the inner city.

marked with heavy dots is the height of the tower, and the number under this is the height of the tower above the ground. Both figures are in meters.

The borders of our inner city toward the west, north, and east, shown by the dotted line in Figure 2, are made up mostly of green parks built on the original fortress walls of the city. To the south, the border runs partly along the Elbe itself and partly along the numerous canals. A small tributary of the Elbe, the Alster, divides the inner city into two approximately equal parts, the old city and the new city. From ancient times, the old city has been the main site of trade in Hamburg. As such, it is interlaced by numerous waterways, the so-called Fleeten, as Figure 2 shows.

These are directly connected to the Elbe, and the water in them rises and falls, corresponding to the tide in the Elbe. The Alster is maintained at a constant height of 3.1 m above standard zero by a lock, shown in Figure 2 by the letter S. This is also the elevation of the water in both of the lake-like expansions of the Alster produced by that lock, the "Binnenalster" which is about 18 times as wide, and the "Aussenalster" which is about nine times as wide. As our map shows, the "Binnenalster" is entirely within the inner city.

Of the eight towers considered in the map, seven belong to churches. The eighth, marked R, is on the city hall. The church towers are marked with the initial of the name of the church: M for St. Michael's, N for St. Nicholas', K for St. Katharine, P for St. Peter, J for St. Jacob (James) and G for the Gustavus Adlophus church. Re designates the two equally high towers of the "Reformed Church", which are only 12 m apart and thus can be considered a single tower for our purpose. /121

The inner of the two circles drawn around each of these eight towers has the radius (h - 25) m. The larger circle has twice that radius. Here, h is the height of the tower in question above the ground. The reason for subtracting 25 m in each case is that it is apparently not a question of the height of the tower above the ground, but the height above the surrounding buildings, which are assumed to have an average height of 25 m.

We shall call these two circles the first and second height circles of the tower in question.

In relation to out theme, we take from the map of Figure 2 the first and most important fact, that not a single one of the lightning strikes entered therein is within the first height circle of the eight towers concerned. Since the same is also true for the more than 20 towers more than 40 m high in the suburbs of our city, we can with some certainty maintain that the protective radius of a tower or post-shaped lightning rod is at least equal to the radius of its first height circle.

On the other hand, even in Figure 2 we find several lightning strikes within the second height circle for the towers of St. Michael's and St. Jacob's churches[2]. Thus we reach a second important conclusion from Figure 2: the protective radius of a tower provided with a lightning rod, projecting 80 - 100 m above its surroundings, is certainly smaller than the radius of its second height circle.

But this latter fact totally disagrees with the protective radius for such a tower-like lightning rod, which was previously calculated from certain theoretical assumptions. According to Table 1, which was calculated on the basis of those assumptions, the protective radius for both these towers should be at least equal to the radius of their fourth height circles.

Furthermore, the strikes in the neighborhood of the Reformed Church in Figure 2 also contradict that theory. This is because, since the two towers project only some 25 m above their surroundings, the radius of their protective circle should, according to Table 1, be about nine times this excess height. Yet Figure 2 shows that it is smaller than the radius of the /122
third height circle for this tower.

Accordingly, it is clear that the basic assumption of my theory, i.e., the assumption that when the lightning leaves the cloud it is directed to the nearest point of the earth's surface, must be false. Rather, we must assume that it takes no notice at all of such a small thing as a tower of 100 m height, even if it is well grounded. This must apply even when the lightning stroke in its jerky progression from the cloud to the earth's surface has approached rather near the earth[3]. Because if we, instead of calculating the size of the protective radius r of such a tower from Formula (1), instead

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[2] The lightning strike shown within the second height circle for St. Nicholas' tower, which I have circled, does not represent a true lightning strike. This will be discussed later.

[3] In this relation, see B. Walter, Ann. d. Physik, Vol 4, No. 10, 1903, page 393, as well as, particularly: Jahrbuch der Hamburgischen Wissenschaftlichen Anstalten, Vol. 20, 1903.

insert into this formula the value r = h from Figure 2, then we obtain for the unknown height H of that point at which the lightning definitely begins to note the tower, the value H = h . That is, this point must be very near the point of the tower. Now let us assume further that r = 2h. According to Figure 2, this is certainly too large for a tower projecting 100 m above its surroundings. Then the formula yields H = 2-1/2 h. That is, the position where the lightning begins to be directed toward the tower is certainly lower than 250 m above the surroundings, or less than 150 m above the point of the tower itself[4].

4. Justification for Explaining the Problem of Lightning Protection with Model Experiments with Long Induction Sparks. Description of Various Tests of this Type

These facts lead to one very important conclusion. We see that experiments with artificial laboratory sparks, which have already been often performed to explain questions of lightning danger and lightning protection, correspond much better to the conditions with lightning than had been assumed so far. In previous tests there had always been a great uncertainty because, as a rule, the height of the house models usually employed was much greater in proportion to the length of the sparks than the ratio of the real houses to the length of a lightning bolt. But from the information above, this difficulty is apparently not present at all, as it is not the entire length of the lightning bolt which comes into consideration for the point of its strike on the earth's surface, but only a small part of its lower end.

Thus we need not refer solely to experience with lightning strikes in the vicinity of city towers to answer questions about our theme. Instead, we can turn to tests with models of such tower-like or post-like lightning

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[4] Incidentally, from this it also appears impossible to draw, from electrostatic observations on the surface of the earth, conclusions about the processes in the storm clouds themselves or, for instance, about the sign of their charge, as has recently been done by C. T. R. Wilson and his students.

rods in a long spark gap. As we shall see in more detail below, this is particularly important for explaining the concurrent operation of several such lightning rods.

With respect to the type of sparks which are most suitable for these experiments, I have already indicated in my works on lightning production, mentioned above, that there is a very great similarity between the mechanism of lightning production and production of sparks of a large induction apparatus. Thus we could expect that such sparks would be especially suitable for explaining questions about our theme.

In order to test the correctness of this conclusion, I first determined whether the same results would be obtained for the protection range of a model of a simple lightning rod using sparks of this type, as we have derived above from Figure 2 for the lightning rods of Hamburg towers. That is, would the protection range of such a model reach to its first height circle, but not to its second one.

The sparks used for making a decision about this question were produced with a spark inductor with a maximum spark gap width of 60 cm. They were always produced as single sparks. The armature of a mercury interrupter in the primary circuit of the apparatus was dipped into its mercury vessel simply by activating it by hand, and then pulled out again. The spark gap was set up so that the point at which its sparks fell would not be affected either by the electrostatic charges in the inductor itself or by the charges in the wires connecting it to the spark gap[5]. It consisted of a smoothly polished horizontal brass disk 35 cm in diameter as the negative pole, 2 /123
meters from the inductor. At the center of this disk there is a brass screw, 2.5 cm high, as the model of a tower lightning rod. The head of the screw is also flat and polished for better contact. The positive pole is a vertical brass rod, pointed at the lower end. The point is 50 cm from the plane of the disk.

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[5] See B. Walter, Ann. d. Phys., Vol. 5, No. 13, 1932, p. 483.

Now, if this rod were set vertically over the center of the negative disk, all the sparks proceeding from it would strike the model lightning rod. But if the positive rod were moved 15 cm laterally from the vertical line through the center of the negative disk, then, with 50 cm separation between this disk and the positive rod, more sparks would go directly to the negative disk than to the model, in spite of the fact that the distance between the model and the positive point was still somewhat less than the distance between that point and the closest point of the negative disk itself[6]. That is, of 400 individual sparks, 285 went directly to the disk and only 115 to the model. Of the 285 sparks, not one struck within the first height circle of the model, but six struck between the first and second, 38 between the second and third height circles, and the rest further outside.

Thus we see that the lightning rod model in our spark gap also protects its surroundings from lightning only out to the first height circle, just as is the case for the lightning rods of the Hamburg towers, according to Figure 2. Thus we have the first example of the fact that, in spite of the great differences in the dimensions of the phenomena in our model experiments, on the one hand, and those of real lightning, on the other hand, we can with some confidence reach conclusions about the conditions occurring in the latter case. We shall identify still another example of this type below.

Another noteworthy factor is that in the model tests just described, a large number of the sparks striking the model itself followed a path like the one shown in Figure 3. That is, very frequently these sparks were directed toward this model only at their lower ends, just as we concluded above for real lightning strokes striking a church tower. In our model tests also, then, the upper end of the spark is hardly to be considered in relation to the place of strike, and the length of the spark gap in these tests is of little difference.

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[6] In respect to the reason for this, see my 1932 treatment mentioned above.

We can derive still another remarkable fact from Figure 2. In the rather extensive region between the five high towers in the old city of Hamburg, not a single damaging lightning strike has occurred during the 21 years in question[7].

If we also consider that a relatively large number of lightning damages have been recorded in the surroundings of the region between those five high towers, we can with a good degree of certainty conclude that those towers almost completely protected the region between them from lightning strokes. This is also understandable from a theoretical standpoint. But it follows from this fact that, by proper combination of several such tower-like lightning rods, the protective range of each of them is considerably increased for the region lying between them.

According to Figure 2, the separation between any two of the five towers in question is greater than the sum of the radii of their first, and in many cases even greater than the sum of their second height circles. Thus we can conclude that, by proper combination of two such tower-like lightning rods, the radius of the protective circle of one, along the connecting line, is somewhat greater than that of its second height circle.

But, on the other hand, a lightning strike is mapped in Figure 2 almost exactly on the connecting line between the towers of St. Michael's and St. /124
Nicholas' churches. Therefore, the lightning rods of these two towers together were unable to protect the building on their connecting line from lightning strokes. The distance between these towers is 810 m, and the sums of the radii of their third and fourth height circles, taken in the

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[7] There is one strike marked on the map, which I have circled and mentioned briefly above. With more detailed inquiry by the insurance office, this proved to be nothing more than slight damage to a power line within one room of a large building, which occurred during a lightning strike. In spite of detailed investigations, no damage could be detected at the roof of the house. For this reason, the questionable case of damage is recorded in the records of the fire insurance office only as "caused by a side effect of a lightning bolt striking in the neighborhood".

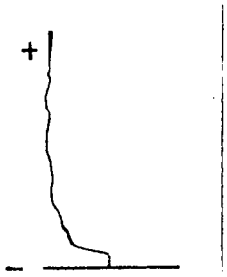

Figure 3. A spark striking the lightning rod model, as seen from the side.

sense defined above, are 687 and 916 m, respectively. Thus it follows that the protective effect of the two towers together, along the line mentioned, is in any case not more than the sum of their fourth height circles.

From these two facts together, it appears that with two post-shaped lightning rods set up an appropriate distance apart, the protective radius for the surroundings of one of them, along their connecting line, is greater than the radius of its second height circle, and less than that of its fourth height circle.

Now, in order to compare these conclusions from Figure 2 with the results of appropriate model tests with induction sparks, two equally high brass screws were set up on the diameter of the negative disk of the spark gap described above. The screws were at equal distances from the center, and the positive rod of the spark gap was always 50 cm above the center of the disk. Then 100 individual sparks were produced with various separations a of the two screws from the center of the disk. Each time, the number n of sparks striking directly on the negative disk was determined. These are the sparks not intersected by one of the two screws. Table 2 summarizes the results of four test series of this type, using four screw pairs of different height h. The results are also plotted as curves in Figure 4. From the Figure we see that the number n of sparks not caught by the two screws decreases very rapidly as the distance between the screws decreases for all four pairs of screws. Thus, with each of the four curves of Figure 3, extrapolation to the abscissa rather accurately gives the separation a_0 for which all of the sparks directed to the vicinity of the connecting line are caught by the four screw pairs used. This separation a_0, which can be designated as the protective radius of each of the screws along the connecting line, is indicated in the next to the last line of Table 2 for each of the four screw pairs. Finally, if

TABLE 2. n INDICATES THE NUMBER OF SPARKS OUT OF 100 SPARKS ABOUT 50 cm LONG NOT INTERCEPTED BY ONE OF THE TWO LIGHTNING ROD MODELS OF HEIGHT h AND SEPARATED BY THE DISTANCE 2a. THIS IS THE NUMBER OF SPARKS GOING DIRECTLY TO THE METAL DISK ON WHICH THE MODELS STOOD.

h =	2,0 cm	2,5 cm	3,2 cm	5,0 cm
	n =			
and a = 4 cm	0		--	--
5 ,,	2			
6 ,,	8			
7 ,,	15			
8 ,,	32	5+	5	
9 ,,	43	17	9	
10 ,,	---	49	15	--
11 ,,		---	37	-
12 ,,	--		61	1
13 ,,	---		--	6
14 ,,	-			20
15 ,,	---		-	55
therefore a_0 =	4,6 cm	6,8 cm	8,4 cm	12,0 cm
and a_0/h =	2,3 ,,	2,7 ,,	2,6 ,,	2,4 ,,

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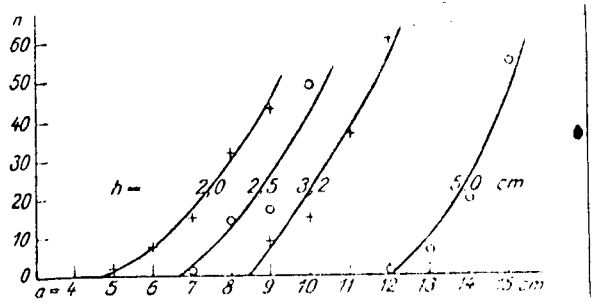

Figure 4. Presentation of the results of Table 4 as curves.

we divide this quantity a_0 by the height h of the matching screw, as is done in the last line of the table, we obtain, as the table shows, approximately the same value of 2.5 for each of the four screw heights used. That is, the protective radius is approximately equal to 2-1/2 times the height of the screw in question.

Therefore, in these model tests with induction sparks, we again arrive at a result which agrees well with that about the protective effect of the towers of the old city of Hamburg. Thus, we can assume it is fairly certain that, for each of two post-shaped lightning rods set up at an appropriate distance from each other, the protective effect for the surroundings along

the connecting line reaches somewhat beyond the second height circle.

5. Most Practical Form of a Remote Lightning Rod System for a Simple House

Of course, it is also of great interest to set up similar spark gap tests with three and more such lightning rod models in a definite arrangement. But for the present I would prefer not to go into the experiments I have performed along this line. Instead, I would like to refer to an example of a result found for two post-like lightning rods at a certain separation, which has great promise in practical applications. This concerns lightning protection for a simple house of the shape shown in Figure 5, as is the case for most thatched houses. Then the part of the house which is by far the most exposed to lightning is obviously its ridge line. From the above it is obvious to protect it, as shown in Figure 5, by means of two vertical lightning rod posts F_1S_1 and F_2S_2 erected at the extensions of both ends of the ridge line. According to the above, the protective effect of one of these two rods extends along their connecting line as far as 2-1/2 times the height by which its point projects above the ridge line of the house to be protected. Thus, if we designate the entire length of the house as 2a, the height of its ridge as c, the entire height of one of the two rods as h, and their distance from the house as d (see Figure 5), then from the above, a + d can be at most 2-1/2 times h - c. That is

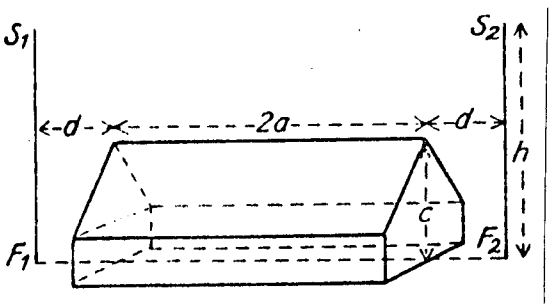

Figure 5. Remote lightning rod system with two rods F_1S_2 and F_2S_2, for a simple house.

$$h \geq c + \frac{a + d}{2{,}5} \qquad (2)$$

For example, if we take 2a = 40 m, c = 15 m, and d = 10 cm, then h must be equal to or greater than 27 m.

It might now be assumed that, instead of protecting the house of Figure 5 with two such remote lightning rods, it would be more practical to erect only one. This would best be erected in the plane through the center of the house perpendicular to its longitudinal direction, like point F of Figure 6, where ABCD represents the ground plan of the house. But then the height of this rod would have to be made considerably greater than that of the two rods of Figure 5, because from the above, the protective effect of a single lightning rod extends only to the first circle of its projecting height.

In order to obtain a general expression for the height of the rod h in this case as well, we must first consider that the most exposed points of the house will then be the two ends of its ridge line. Thus, if the dotted line EG represents the ridge line of the house in Figure 6, the most exposed points are E and G. Now let us call the width of the house 2b, retaining the other designations of Figure 5. Therefore, in the case of Figure 6 the projecting height h - c of the rod must be at least as great as the line EF, if we now consider F to be that point of the lightning rod which is at the same height as the ridge line EG. But now EF = $\sqrt{a^2+(b+d)^2}$, so that the general relation

$$h \geq c + \sqrt{a^2+(b+d)^2} \qquad (3)$$

applies for the height of the lightning rod in Figure 6.

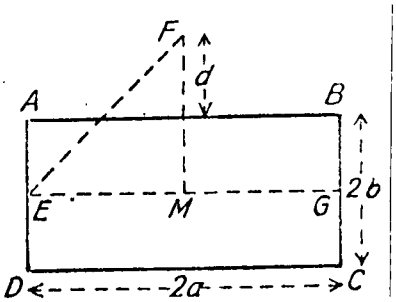

Figure 6. Remote lightning rod system with a single rod erected at F for the house of Figure 5.

In the example above, where c = 15 m and 2a was 40 meters, if we set the width of the house, 2b = 20 meters and also assume as before, that the distance of the rod from the house = 10 m, then h must be equal to or greater than 43.3 m. Therefore, the lightning rod is considerably higher than both of those in Figure 5. We should also mention here that with the two rods of Figure 5 the protection of the house is completely symmetric, not only in the longitudinal but also in the transverse direction, while with the rod of Figure 6 the half of the house turned away from it is less well protected than the side turned toward it.

Finally, I would also like to discuss the grounding of our remote lightning rod. It must be particularly noted that this grounding must be /126
at least as good as that for each point of the building to be protected. Thus, if the building contains a gas or water line, then our lightning rod must in all cases be bonded to these lines. A buried connection is sufficient here, as all the points of the house above the ground are in the protective range of our lightning rod.

If there are no lines of the type mentioned in the earth adjacent to the building, then the same rules apply for grounding our remote lightning rod as for the previously used lightning rods. These are extensively described in the well-known guidelines of the Committee on Lightning Rod Construction.

Summary

Instead of the currently common type of lightning protection, lightning protection by "remote lightning rods" is recommended to keep the lightning as far as possible from a building and its inhabitants. These "remote lightning rods" are rods which are set up completely separate from the building to be protected. The required height for these rods is derived partly from the lightning strike statistics of the Hamburg fire insurance office and partly from model experiments with long induction sparks. Finally,

the most practical form of remote lightning rod systems for a simple house having the shape shown in Figure 5 is discussed.

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